Broad and Asymmetric Atomic Spectral Lines from Rapidly Spinning Neutron Stars

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Neutron Star

Neutron star vs. a city

Figure courtesy M. Coleman Miller

Radius ~ 10 - 20 km

Mass ~ 1.4 - 2.0 solar mass

Core density ~ 5 -10 times the nuclear density

Magnetic field ~ 10^{7} - 10^{15} G

Spin frequency (in some binary stellar systems) ~ 300 - 600 Hz

Some of the most extreme conditions of the universe exist in neutron stars.

Neutron Star: Surface and Interior

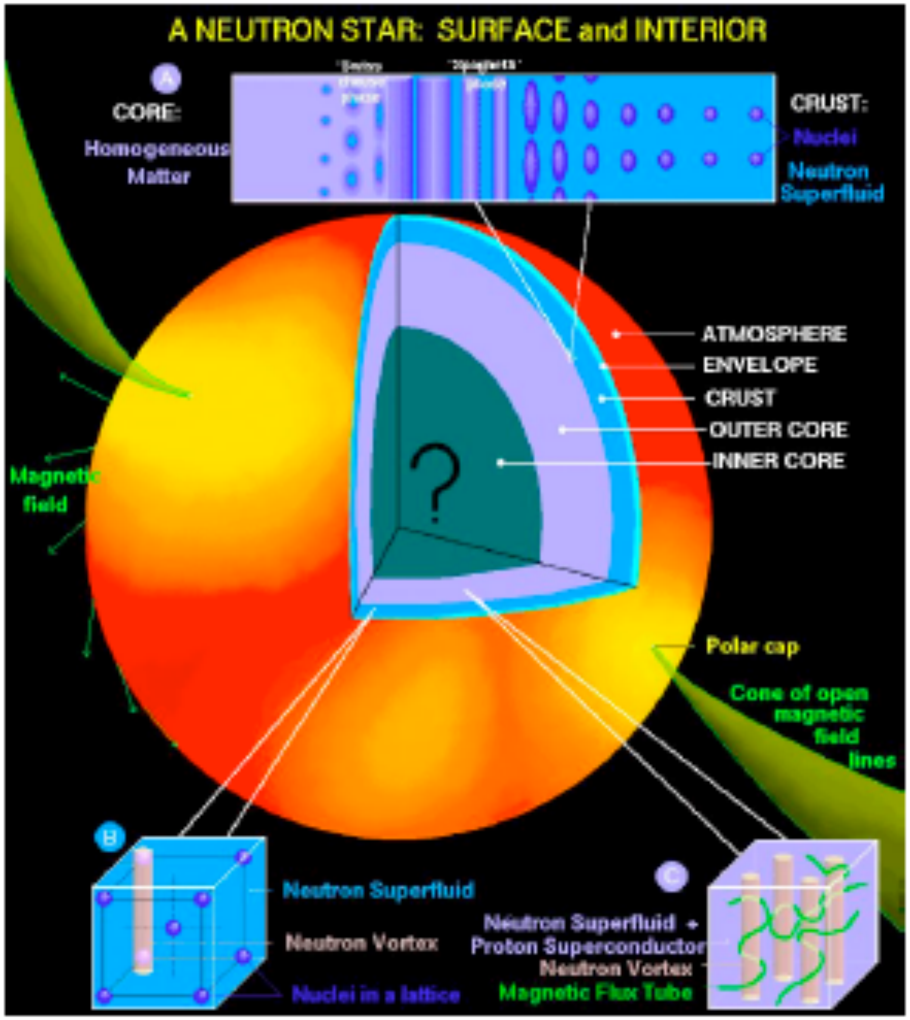

Figure courtesy D. Page.

Core density ≥ nuclear density

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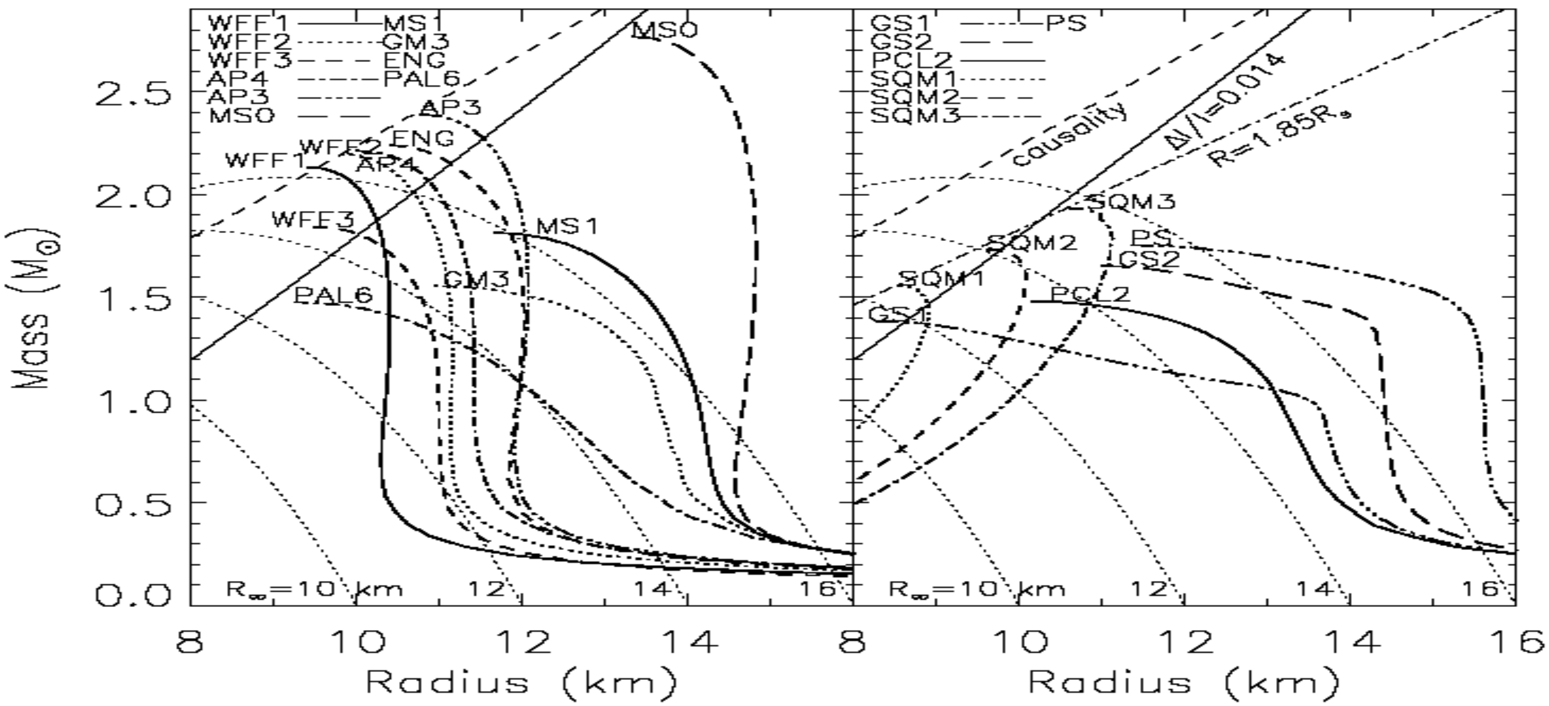
Exotic matter???

No terrestrial experiments seem possible at such high densities and low (comparatively) temperatures.

Many equation of state (EOS) models for the neutron star core matter are available in the literature. We need to constrain these models by observing neutron stars.

The constituents of neutron star interiors remain a mystery after 35 years.

How to constrain EOS models?



Lattimer & Prakash (2001)

Mass, radius and **spin frequency** of a neutron star are to be measured in order to constrain **equation of state** models.

Surface Spectral Lines

Observation of surface atomic spectral line at the energy E_{obs}

$\Downarrow$

Identification: original line energy = E_0

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Gravitational redshift $1+z = E_0/E_{obs}$

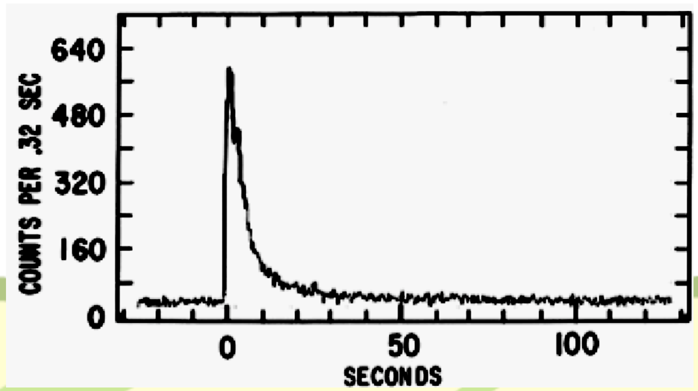
$\Downarrow$

Neutron star “radius to mass” ratio from $1+z = [1-(2GM/Rc^2)]^{-1/2}$

But why LMXBs and Thermonuclear X-ray bursts?

Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release ≈ 10^{39} ergs

Burst light curve



Why LMXBs and X-ray bursts?

* For isolated neutron stars, heavy elements may not exist in the atmosphere. For LMXBs, and during bursts, continuous accretion and radiative pressure may keep heavy elements in the atmosphere for the time required for spectral line detection.

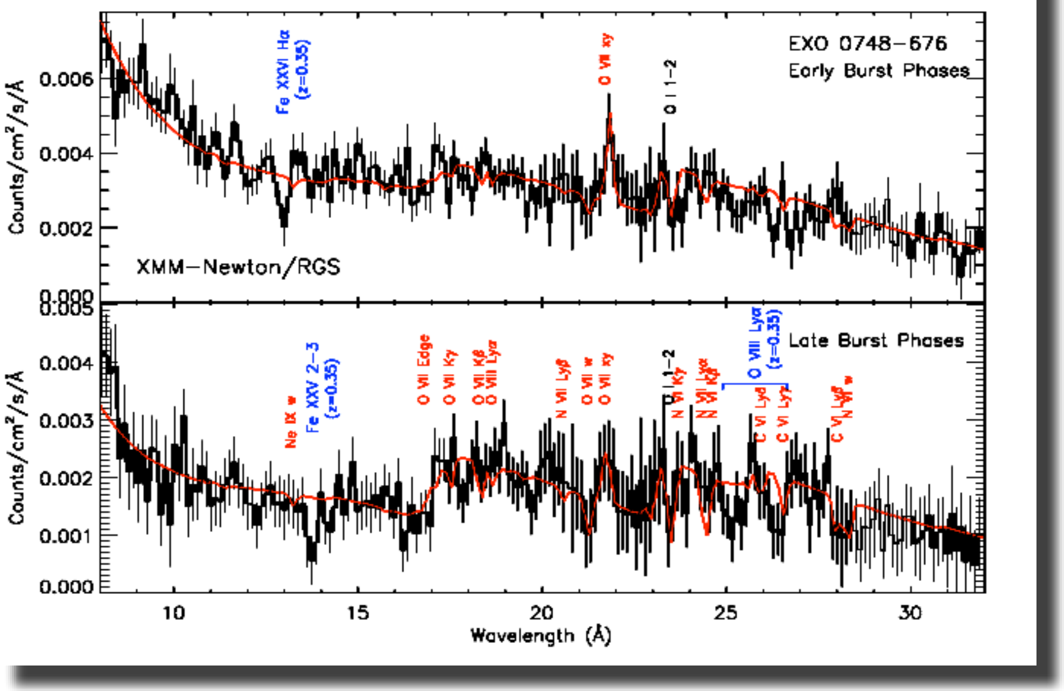
* Comparatively lower magnetic field (10^7-10^9 G):
  (1) magnetic splitting is negligible: line identification is easier;
  (2) magnetic field does not complicate the modeling of neutron star atmosphere and photon emission.

* During the bursts, neutron star surface emission dominates the total X-ray emission.

* During the bursts, high photon flux from the neutron star surface provides good signal-to-noise ratio.

Observational Evidence

Cottam, Paerels & Mendez (2002)



XMM-Newton grating observations of surface atomic spectral absorption lines during X-ray bursts from an LMXB (EXO 0748-676): measured gravitational redshift $1+z = 1.35$, and hence $Rc^2/GM = 4.4$.

Effects of neutron star spin

✼ But the neutron stars in LMXBs normally spin very fast (ν_{spin} ~ 300-600 Hz) due to accretion induced angular momentum transfer.

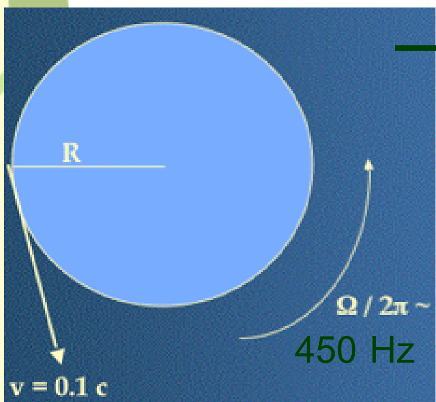


Figure courtesy F. Ozel.

→ *Spinning neutron star:* surface speed is ~ 0.1c; Doppler effect will make the spectral line broad and asymmetric.

How do we measure Rc^2/GM from a broad and skewed line?

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$E_{obs} = (E_1 E_2)^{1/2}$

$1+z = E_0/E_{obs}$

$Rc^2/GM = 2.(1 - (1+z)^{-2})^{-1}$

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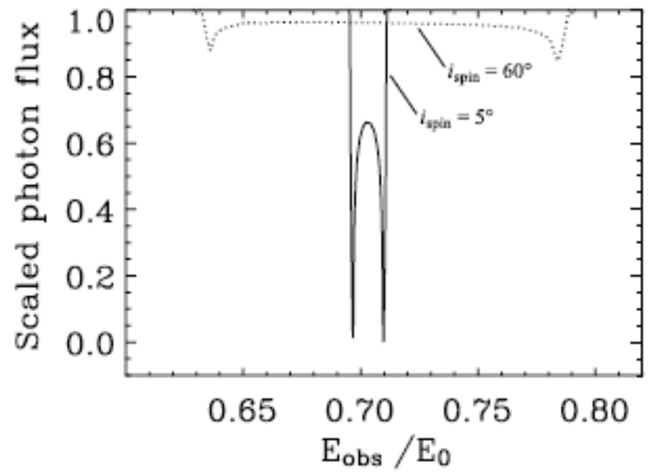
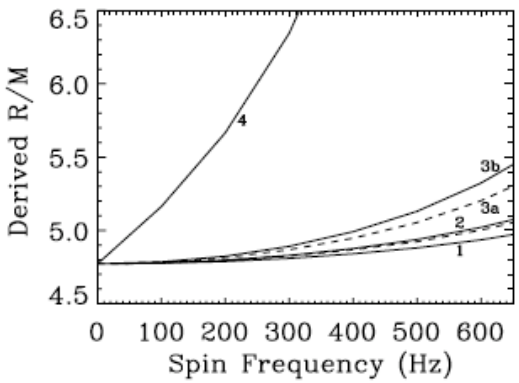
← Better than 2% estimate!



Bhattacharyya, Miller & Lamb (2006)



Bhattacharyya, Miller & Lamb (2006)

Now we are ready to determine Rc^2/GM, when we observe a broad and skewed surface spectral line.

Other parameters and frame-dragging

Neutron star radius from line width:

$$v_{spin} = 2\pi.\nu_{spin}.R.\sin i_{spin}$$

Red-wing flux / Blue-wing flux

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Detection of frame-dragging

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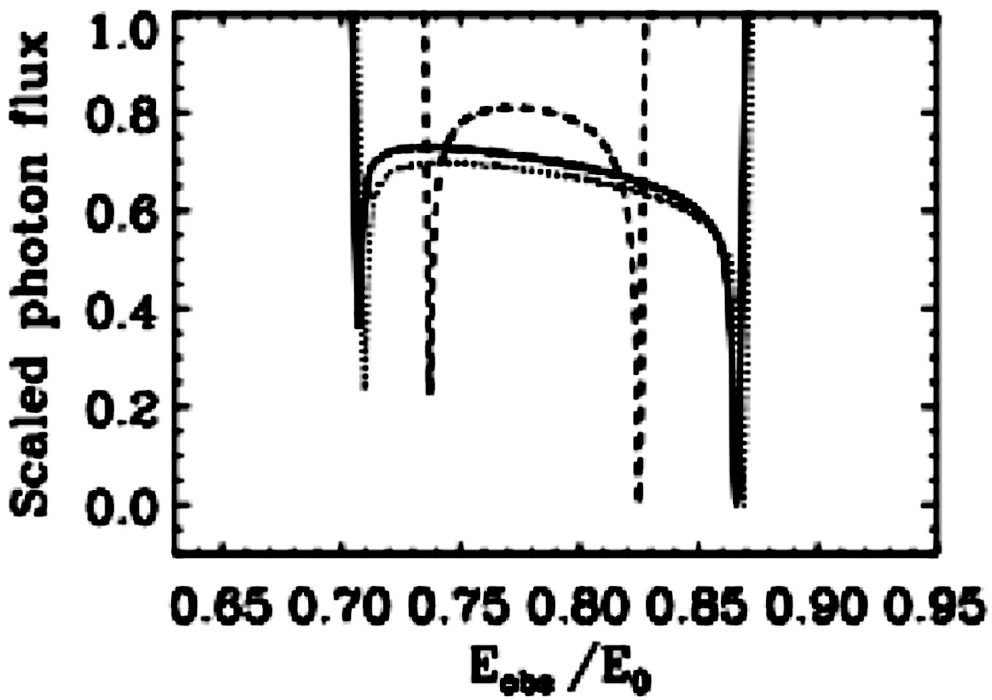
Strong-field test of general relativity



Bhattacharyya, Miller & Lamb (2006)

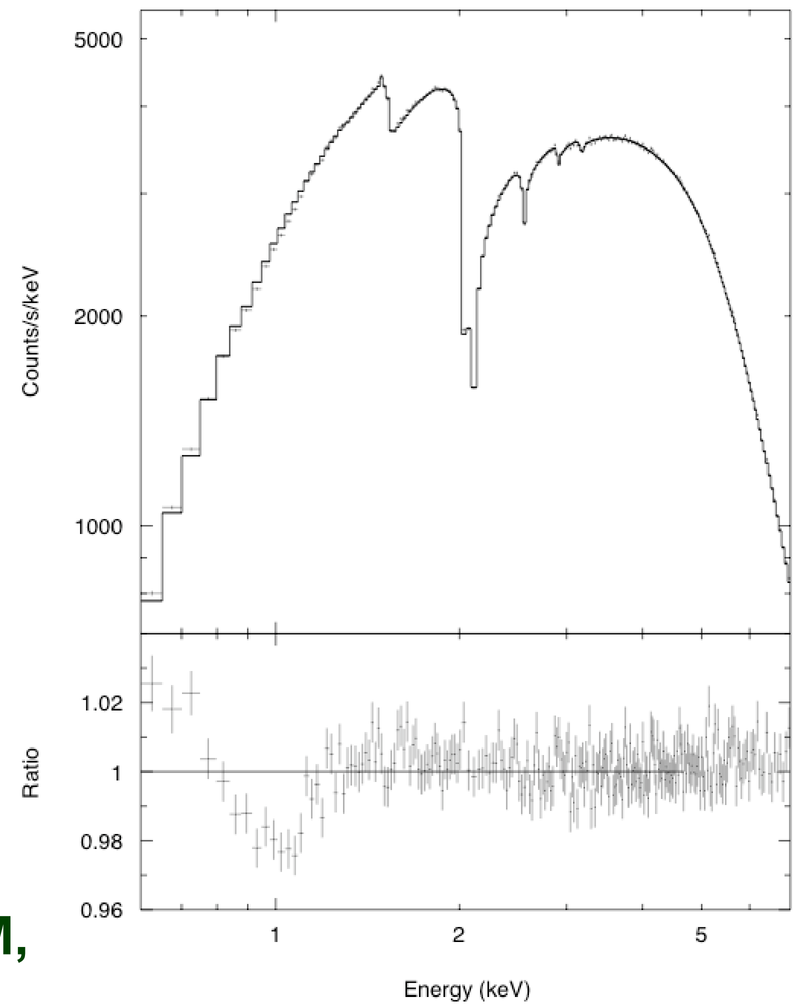
Simulation with XMS response matrix
Detection of broad line

Burst exposure = 800 s
Count rate ≈ 9000 cps

Continuum → Blackbody
(T_{BB} = 1.8 keV)

Line width
⇓
M = 1.4 M_{sun} , R = 10 km ,
ν_{spin} = 450 Hz , i_{spin} = 78°

Line equivalent width ≈ 10 eV



Can constrain neutron star Rc^2/GM, and possibly R.

Simulation with XMS response matrix
Measurement of broad line

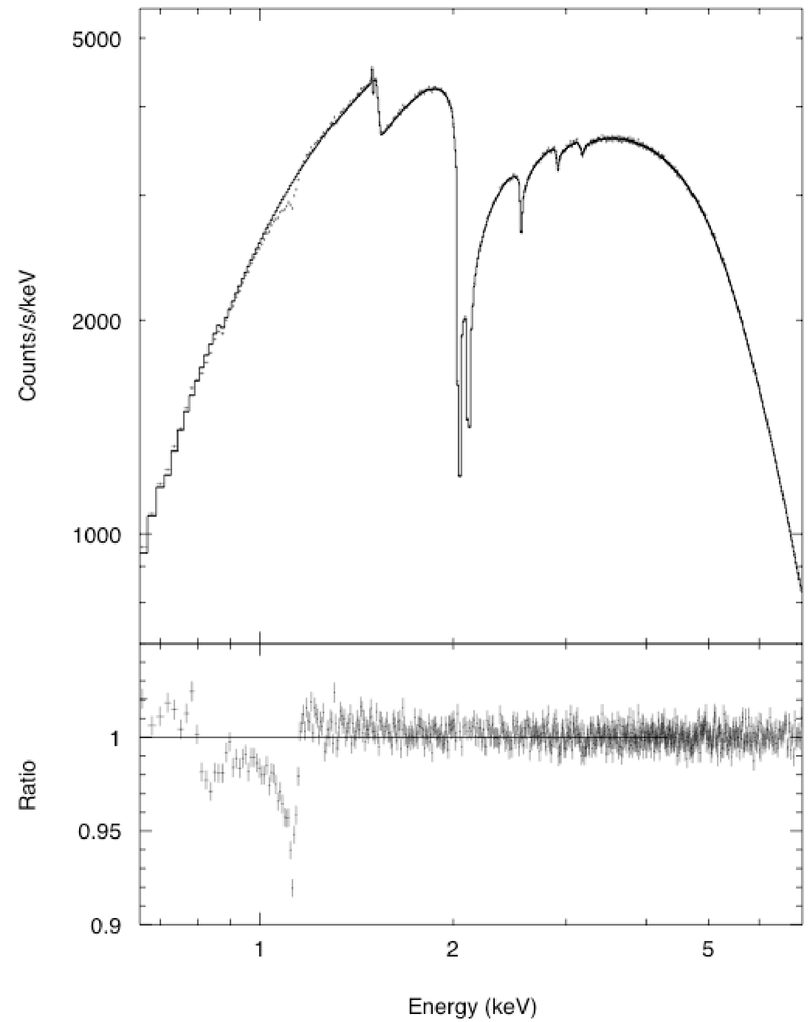
Burst exposure = 3200 s
Count rate ≈ 9000 cps

Continuum → Blackbody
(T_{BB} = 1.8 keV)

Line width
⇓
M = 1.4 M_{sun} , R = 10 km ,
ν_{spin} = 450 Hz , i_{spin} = 78^o

Line equivalent width ≈ 10 eV

Other source parameters, and frame-dragging.



Conclusions

Con-X can detect spectral lines from neutron star surfaces, and measure their shapes with reasonable exposures.

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1) Constraining neutron star parameters.
2) Detection of frame-dragging.

❊❊❊ Thank you! ❊❊❊